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COMPOSITE MATERIALS. I.

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16. Abstract

The paper briefly examines the basic definition of a composite material and characterizes the main types of composites. Mention is made of particle dispersed composite material, fiber reinforced composites (with either discontinuous fibers or continuous fibers arranged unidirectionally or in cross-ply), and laminated composites. Tables are presented showing the mechanical properties (density, tensile strength, specific strength, tensile modulus, and specific modulus) for the most common materials used for fiber (including aluminum, titanium, steel, beryllium, E glass, S glass, carbon, and boron), for whisker (including copper, nickel, iron, B4C, and SiC, and graphite), and for the matrix (including thermoplastics such as nylon, polycarbonate, polystyrene, and metacryl, the thermoset plastic polyester, and aluminum and copper). The fiber efficiency was calculated for reinforced plastics under different fiber orientations, fiber lengths, fiber volume fractions, composite strength, and fiber stress.

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COMPOSITE MATERIALS. I*

Taichi Fujii**

1. PREFACE /1153***

Research and development in the field of materials goes on perpetually. Of various materials, the currently most rapidly developing and noteworthy are composite materials. In this lecture, I would like to focus on the present status of the materials pertinent to this newly developing area by surveying the development of these new materials and their dynamic characteristics. Considerations given in this lecture will center around the current uses of composite materials, and the roles they are playing.

2. SIGNIFICANCE OF COMPOSITE SAMPLES

2.1 Formation of Composite Samples

The history of the development of materials is represented by a

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rise and fall of various types such as stone, lumber, copper and its alloys, iron, steel, and light metals. Among these, it has been known that what would correspond to the composite materials of today was already in use in ancient times, as exemplified by walls of straw mixed in plaster used in dwellings of ancient Egypt, the brick containing pieces of straw used by ancient Israelis, the dry lacquer Buddha of ancient Japan made of hemp fibers immersed in lacquer, and the sculpture using a certain type of clay in which mica particles are mixed. These combinations created materials with characteristics which would have been unattainable by single materials.

We consider that characteristics of materials, such as strength, hardness, anticorrosiveness, antiwearing property, lightness, durability, thermal properties (thermal insulation and conduction), sound insulation property, aesthetic appeal, etc., are desirable characteristics of materials for various uses. Needless to say, this multitude of characteristics could not be fulfilled by single materials, or would be extremely difficult at best. It naturally follows that materials appropriate for different uses could be made by a combination of various single materials. If a value of certain physical property of a composite material is designated as Y, and variables as X_1, X_2, ..., then generally the following relationship is obtained:

$$y=f(x_1, x_2, \cdots\cdots)$$

However, if there is a linear additive property, the relationship is:

$$y=c_1x_1+c_2x_2+\cdots\cdots$$

When X_1, X_2, ..., is taken as the content per unit volume of component materials, C_1, C_2, ..., become the value of a certain physical property of component materials. In actuality, however, there are synergistic and offsetting effects among the component materials, and thus the relationship is not that simple. Weight, modulus of elasticity, and strength could be expressed by this formula of linear additive property.

Accordingly, in order to improve the characteristics of composite materials, each component must have good characteristics. However, it is not necessary to have a component material which in itself could be rendered for a practical use, but it would be sufficient if such a material, in conjunction with others, could be formed into items for a practical use, such as pillars and panels. Based on such a premise, the use of composite materials with high molecular weight and light weight substances with anticorrosive properties as the matrix, and high strength, high elasticity fibers developed toward the end of World War II. This was the inception of the development of composite materials of the fortified fiber type, which has led to the great advances as are seen today. However, advances are still being made with materials, and studies are being carried out from various standpoints on the effect of combinations, so that further advances in material characteristics are to be expected. Thus the composite materials are considered to be still growing and developing.

As has already been mentioned, there are various factors for an evaluation of characteristics of compound materials. Of these, the one of special importance is the ratio between strength and density (σ/ρ), namely, the ratio of strength. Figure 1 shows variations of strength ratios of different materials by year [1], from which one can see the remarkable improvement of strength in the composite materials of the fortified fibrous type.

Furthermore, the ratio between modulus of elasticity and density (E/P), namely, the ratio of modulus of elasticity, is another important factor. Figure 2 shows the ratio of strength on the ordinate, and the ratio of modulus of elasticity on the abscissa.

In the figure, specific values for various materials are shown as rectangular areas because of the varying ratios of ingredients. /1154
The farther one goes away from the origin of the coordinate axes, the higher the performance to be obtained.

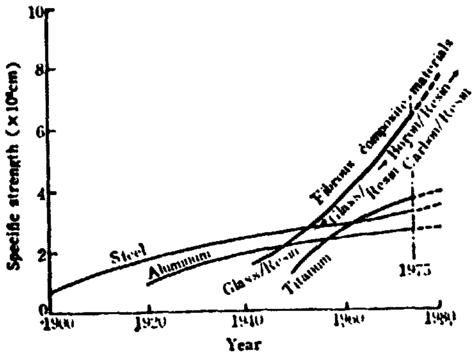

Figure 1. The changes of specific strength of various materials during past 75 years.

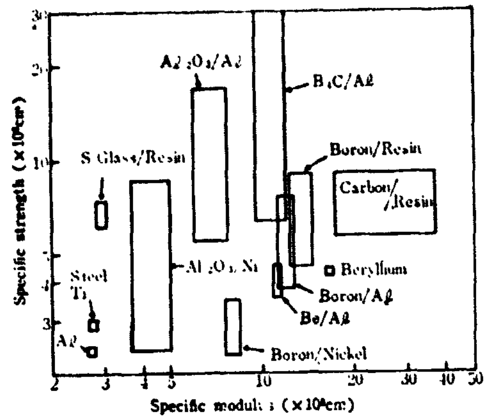

Figure 2. Comparison of specific strength and specific modulus of various materials.

2.2 Definition and Types of Composite Materials

A combination of more than two types of materials to obtain characteristics unattainable by single materials is called a composite material. To put it more concretely, it is a combination of at least two chemically different substances, with a clearly defined interface separating the materials.

Usually a composite sample is made up by dispersing a certain material, made into small particles with a specific form, in another material. The former is called the dispersed phase, and the latter - the matrix phase. Since the dispersed phase determines the characteristics of a composite material, the following classification could be made:

particle dispersed composite material
fiber reinforced composite material.

Furthermore, in actuality, sheets or panels of these composite materials are often layered and glued to form laminated composite materials. Figure 3 and Table 1 show combinations and illustrations of these composite materials.

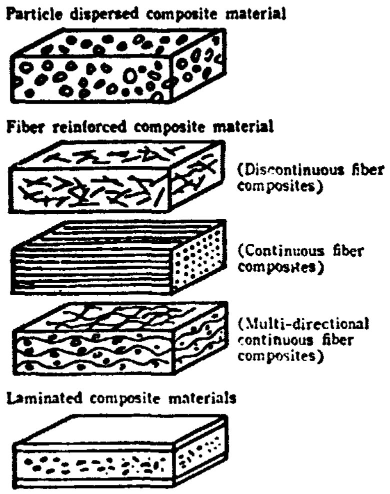

Figure 3. Kinds of composite materials.

TABLE 1

COMBINATION OF MATERIAL IN COMPOSITES

Form of dispersed phase	Kind of material of matrix phase	Name of composites
Particle, powder	Rubber	PRR, FRR
Fiber	Plastics	FRP
Discontinuous short fiber	Metal	FRM, PRM
Continuous long fiber	Ceramics	
Flake		FRC

PRR : Particle reinforced rubber
FRR : Fiber reinforced rubber
FRP : Fiber reinforced plastics
FRM : Fiber reinforced metal
PRM : Particle reinforced metal
FRC : Fiber reinforced ceramic

3. FIBER REINFORCED COMPOSITE MATERIAL

It has been known that when a material such as glass is made into a fiber form, the internal defects become less and strength increases as the radius is decreased. Also, when crystalline materials are made into fine fibers, the directions of the axes of the crystal and the fibers coincide. Especially in cases such as whisker crystals, rearrangement is minimal, and a very high degree of strength could be obtained. The most frequently used fibers at this time are glass fibers. Ordinary plate glass has a strength of around 7 kg/mm^2, whereas fine fibers of glass attain a strength of 280 - 500 kg/mm^2.

In addition to glass fibers, various other fibers are used. Table II shows characteristics of such fibers.

The fibers could be used continuously and discontinuously in matrices. In the former, the fibers are used in sheet form or delineated in certain directions by methods such as winding formation. In the latter, fibers are cut into pieces several centimeters in length, and used in a mat form.

TABLE II
PROPERTIES OF VARIOUS FIBERS

Kinds of fiber	Density (kg/cm³)	Tensile strength (×10³kg/cm²)	Specific strength σ/ρ (×10⁶cm)	Tensile modulus E(×10³kg/cm²)	Specific modulus E/ρ(×10⁸cm)
Metallic material					
Aluminum	0.00269	63.3	2.36	7 452	2.733
Titanum	0.00471	196.8	4.18	11 740	2.493
Steel	0.00781	421.8	5.40	21 000	2.689
Beryllium	0.00186	175.8	9.47	30 930	16.666
Inorganic material					
E glass	0.00255	351.5	13.80	7 382	2.897
S glass	0.00249	492.0	19.74	8 789	3.525
Carbon (high strength)	0.00175	250~350	14.3~20	20 000~25 000	11.4~14.3
Carbon (low strength)	0.00195	200~250	10.3~13	35 000~38 000	17.9~19.5
Boron	0.00258	351.5	13.65	42 180	16.374
Organic material					
PRD-49	0.0020	170~225	8.5~11.3	13 300	6.65

TABLE III
PROPERTIES OF WHISKERS

Kinds of material	Density (kg/cm³)	Theoretical strength σ_T(×10³kg/cm²)	Measured strength σ_E(×10³kg/cm²)	σ_E/ρ (×10⁶cm)	Tensile modulus E(×10³kg/cm²)	E/ρ (×10⁸cm)
Copper	0.0089	1 265	302.3	3.396	12 654	1.422
Nickel	0.0089	2 179	393.7	4.423	21 793	2.449
Iron	0.0078	2 039	1 335.7	17.124	20 387	2.614
B_4C	0.0025	4 570	681.9	27.276	45 695	18.278
SiC	0.0032	8 436	1 124.8	35.15	85 766	26.802
Al_2O_3	0.0039	4 218	1 968.4	50.47	42 180	10.815
Graphite	0.0016	9 982	2 109.0	131.8	99 826	62.391

Also of interest as an example of reinforced fiber is a whisker. The whisker is a needle-shaped crystal which was developed initially by the General Electric Company of the U.S., in 1960, as the alumina whisker (Al_2O_3 whisker). Subsequently ceramic whiskers such as BeO, B_4C, SiC, Si_2N_4, and carbon, and metallic whiskers such as copper, nickel and iron, have been developed. Their diameters are 0.2-3μ, and lengths are 2-25 mm. Recently trial products have been made in which fibers are incorporated in a matrix in a continuous manner.

TABLE IV

PROPERTIES OF VARIOUS MATRIX

Kinds of material	Density ρ (kg/cm^3)	Tensile strength σ ($\times 10^3 kg/cm^2$)	Specific strength σ/ρ (cm)	Tensile modulus E ($\times 10^2 kg/cm^2$)	Specific modulus $E\rho$ ($\times 10^2 cm$)
Thermoplastics					
Nilon (6/6)	1.14	703	616.7	280	245.6
Polycarbonate	1.20	668	556.7	225	187.5
Polystyrene	1.05	457	435.2	280	266.7
Vinyle-chloride	1.4	600	428.6	300	214.3
Metacryl	1.4	720	514.3	280	200.0
Thermoset plastics					
Polyester	1.1	410	372.7	380	345.5
Metal					
Aluminum	2.7	700	259.3	7 200	2 667.0
Copper	8.65	2 500	289.0	12 500	1 445.0

Table III shows an example of characteristics of the whiskers.

The matrix of a reinforced fiber composite material plays the important role in supporting weights, preventing external deteriorating influences, and transmitting forces through the interface with /1155 the fibers. For the matrices, various materials such as high molecular weight substances, inorganic substances, and metals are used. Table IV shows their characteristics.

The dynamic properties of composite materials are determined by the fibrous component. Figure 4 shows to what extent the strengths of the fibers themselves are utilized [3], and it could be shown that the forms, directions and dimensions of the fibers cause some difference in strengths.

4. PARTICLE DISPERSED COMPOSITE MATERIALS

These are materials with a particulate dispersed phase. As special situations, the dispersed phase composed of small pieces, that is, flakes, could be included. When the diameter of particles is 0.1-0.01 μ, the materials could be called dispersion strengthened composite materials. When the diameter is 1-50 μ, they are called particle reinforced composite materials. By combining with various /1156 matrices, there are a wide variety of materials in practical use.

Material (epoxy resin matrix)	Fiber orientation	Fiber length	Fiber volume fraction (V_f)	Composite strength (kg/mm²)	Calculated(*) fiber stress (kg/mm²)	Fiber efficiency (**)
Nonwoven unidirectional laminate		Continuous	0.47	112.5	229.9	82%
Nonwoven crossply laminates		Continuous	0.47	52.7	202.5	72%
E Glass fabric, Style 181, Volan finish		Continuous	0.60	39.2	126.5	45%
E Glass fabric, Style 181, HTS finish		Continuous	0.59	50.8	163.1	58%
Chopped fibers		12.5 mm	0.48	19.0	118.8	42%

(*) Fiber stress calculated from the volume percent of fibers in the load direction.
(**) Fiber efficiency—calculated fiber stress at failure/assumed fiber strength (281 kg/mm²)

Figure 4. Fiber efficiency of reinforced plastics.

4.1 Nonmetal Particles--Nonmetal Matrices

Here, the particles could be inorganic or organic materials, and the same is true for the matrices. An example of inorganic particles and inorganic matrices is concrete, in which sand and gravel are combined by a mixture of cement and water, utilizing the chemical reaction between cement and water to cause hardening. In this situation, if organic substances are used for the matrices, such materials are exemplified by resin mortar and resin concrete. The dispersed phase of the former is sand, and the latter is sand and gravel. The matrix in both cases is organic resin, which frequently contains micro-particles of calcium carbonate. The particles have been shaped irregularly, but recently spherical and hollow spherical particles are being developed, which could be used for the dispersed phase. These spheres are made of glass, high molecular weight substances, carbon, etc.

4.2 Metal Particles--Nonmetal Matrices

When metal particles or flakes are dispersed in high molecular weight substances, thermal conduction is increased, thermal expansion is reduced, and wear is decreased. Thus there are materials such as copper and silver dispersed in epoxy resin to improve electric and thermal conduction. The material in which powdered aluminum is dispersed in polyurethane is used as a rocket propellant.

4.3 Metal Particles--Metal Matrices

In this combination, the metal particles in the dispersed phase could be harder or softer than the metal matrices. The former could be attained by the use of particles of tungsten, molybdenum, or chromium. These are brittle materials, but because of their good heat resisting property, strong materials with good heat resistance could be obtained by using materials high in tenacity as the matrices. An example of the latter combination, with softer particles in harder matrices, is lead particles dispersed in copper alloys or iron. This type of combination improves workability with machinery and tools.

4.4 Nonmetal Particles--Metal Matrices

The materials combined with metallic matrices are worked on frequently at a high temperature, so that ceramic materials are used for the dispersed phase. The so-called Thermet belongs to this type. Here, the dispersed phase particles could be oxide and carbide. Tungsten carbide in the cobalt matrix attains a very high hardness, and this material is used for wire drawing and valves. When chromium carbide is used, antiwear and anticorrosive properties are quite good, and the resulting materials have thermal expansion coefficients close to that of iron, thus rendering such materials suitable for use in valves. Materials using titanium carbide have excellent thermal resistance, so that they are suitable for use in the parts of a turbine which are subjected to high temperatures.

5. LAMINATED COMPOSITE MATERIALS

When the reinforcing materials are dispersed in matrices to form plates (or curved shells), these are called lamina. The process of layering and adhering them together is called laminating, and the product of such a process is called laminates. Individual laminae in a laminate are arranged in various direction, according to the status of the dispersed phase, that is, the directions of the dispersed fibers for reinforcement. Schematic diagrams of the foregoing are presented in Figure 5. The so-called clad material, sandwich structure, etc., could be termed laminated composite materials in a broad sense.

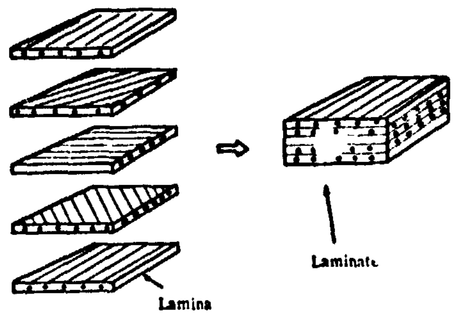

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Figure 5. Lamina and laminate.

6. THE SYSTEM OF ENGINEERING OF COMPOSITE MATERIALS

As described above, the engineering of composite materials covers a broad area, and this is not different from other fields of engineering. However, there are fields of technology specifically developed for composite materials such as methods of composition and study of dynamic behavior. New methods of studying dynamic behavior of composite samples are being developed. It follows then to determine how well these areas of engineering have been systematized. In answer to this question, it could be said that remarkable developments have been seen in study of dynamics and strength of composite materials, research into new types and formation of materials, structural designing making the optimal use of composite materials, evaluation of reliability and characteristics of materials, and their practical applications.

Since composite materials now could be used as the main structural material where strength and rigidity are required, designing for their optimal use, utilizing their characteristics of light weight, resistance to water and chemicals, has become an urgent need. In order to summarize the current status of the engineering science of composite materials, characteristics of particle dispersed and fiber reinforced composite materials are compared in terms of several items of evaluation, as shown in Table A [2].

In composite materials, as has been mentioned in the definition, interfaces are present and they play significant roles in the functions of composite materials [3].

While there is a great deal of expectation for composite materials in material science, total systematization of the field is not complete as yet. Composite materials are "man made," and as such they must be scientifically systematized as rapidly as possible. In this lecture series, starting the next time, I plan to cover subjects such as materials and their formation, interfaces, dynamic behavior, static and dynamic strength, and reliability in light of various problems and differences in methods of treatment that were not thought of with simple materials.

TABLE A (Continued)

TYPES / TYPES OF EVALUATION	PARTICLE DISPERSED COMPOSITE MATERIALS		FIBER REINFORCED COMPOSITE MATERIALS
	MICRO PARTICLE SIZE $d_p = 0.01 \sim 0.1\mu$	PARTICLE SIZE $d_p = 1 \sim 50\mu$	
Dynamic characteristics of comp. materials	Isotropy	Isotropy	Anisotropy
Interface characteristics	Important, but only small influences on strength	Important	Important with discontinuous fibers
Methods of formation	Powder metallurgy, oxidation, electrochemistry, extraction, etc.	Granular metallurgy, permeation, casting, etc.	Granular metallurgy, vacuum permeation, undirectional coagulation, electrochemistry, filament winding, formation under high pressure, etc.

Where d_p: particle diameter; D_p: interparticle distance; mfp: mean free matrix path, V_p: proportion of particles by volume; V_m: proportion of matrix by volume; L: length of fiber; L_c: limit of fiber length; d_f: diameter of fiber, V_f: proportion of fibers by volume.

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